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High efficiency DC-DC converters including a performed recovering leakage energy switch

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Abstract

In this paper we studied the possibility to use high voltage DC bus to facilitate the energy transport in the smart grids, especially oriented to renewable energies. Recent studies [1] show that it is necessary to increase the output voltage in order to minimize transport losses on high distances. That is possible if we use electronic systems able to convert with a high efficiency the low voltage delivered by the local generators constituted by the Pv panels, the wind generators and other ones systems in various power ranges, and providing a high output voltage. In our study we expect to reach a voltage up to $5kV$ and more. The facilities offered by the DC bus are essentially in a very easy full synchronization and the possibility of communication supported by the power lines as in a PLC mode. So, as a consequence, it is important to improve the DC-DC converters to reach more than $5kVDC$ at the output. The main difficulty encountered when the goal is to increase the voltage in a smart DC-DC converter, is the small volume usable of those converter, the low cost, and of course the higher efficiency as possible. High voltage elevation implies the use of specific transformers (THT transformers) with a high voltage isolation performance, and a specific coils configuration to avoid spark discharges. The use of high voltage transformers ineluctably implies lower coupling coefficient between the coils, and undesirable superposed oscillations in the primary and secondary currents and voltages. More over the low coupling factor implies an increasing of the internal energy stored in the leakage inductors, that must recycled in order to keep a good efficiency. Previous studies [2] show the interest of using light structure converters based on one driven switch as the basically step-up boost. Some improvements [3] allow an expanding range working, and more specifically in the high value V_{out}/V_{in} of the converter ratio. We demonstrate in this paper that it is possible to use low coupled coils transformers to insure a perfect control and management of the energy without worrying about the leakage non-transferable energies stored in the various distributed inductors.

Keywords: Photovoltaic, converters, HVDC, Solar, Power MOSFET, Push-Pull, Boost, Inverter, DC-DC converter, Step-Up, coupled coils.

1. Introduction

In the past, various DC-DC converters were proposed to insure a dependable and efficient elevation voltage [4]. It was anteriorly described in papers [5] that a MCB DC-DC converter type as shown in Fig. 1a is very efficient for powers in the range of few hundred watts. A decisive improvement was also proposed [6] to recycle the energies variously

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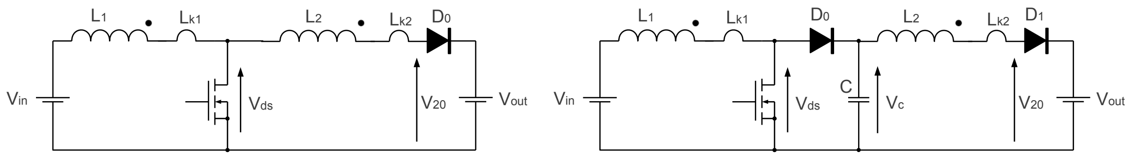
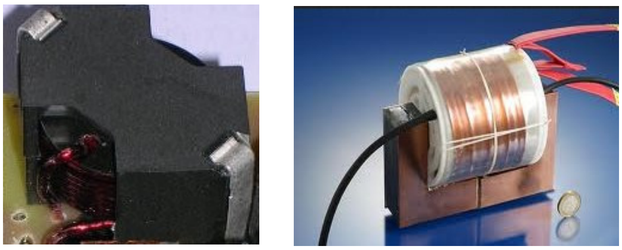
stored in the leakage coupled coils as shown in Fig. 1b. This very efficient and attractive structure is well suited for the HVDC applications [7] in the distributed power production, and moreover when the included elevator transformer is especially manufactured with strongly magnetically coupled coils. At the reverse, if we use a low coupling factor (k) for the high voltage transformer, a critical problem of the stored leakage energy in the parasitic inductors appears. As the theory predicts, as shown further in this paper, the intermediate recovery voltage on the storing capacitor C increases drastically due to a surplus flow of non-transferable energy in the coupled coils. To resolve that problem, an improvement will be proposed by adding to the initial structure a second MOSFET M_2 in parallel with the diode D_0. This secondary MOSFET M_2 can be driven in synchronisation with the first one. It can then assume two roles when it is in the onstate: a) Assist the direct mode working by decreasing the direct voltage shut-down of the diode D_0, b) Allow the flow back of the exceeding of the leakage energy stored in the C capacitor to the primary generator.
The drawbacks of the high voltage transformers is the lower coupling coefficient between the two coils than in a traditional core transformer as shown in Fig.2a and Fig.2b. As represented in Fig.3, a non ideal transformer is equivalent to a perfect one added with parasitic inductors representing the effect of the magnetic leakage flowing out of the magnetic circuit. Those parasitic inductors in series with the transformer inevitably produce some superposed oscillations in the primary and secondary currents and voltages too. More over the low coupling factor implies an uncontrolled increasing of the intermediate recovery voltage V_c in the MCB boost (see Fig.2b).



a) b)

Figure 1: a) Basic MCB converter, b) Improved MCB with recovery stage.

Recently our study shown that there is an optimal coefficient for the coupling factor below which it is not possible to insure a V_c voltage stabilization low enough to secure the MOSFET M_1. In our case, we consider that the coupling factor (k) can reach a low value down to 70%, that constitutes a serious problem to assume the correct management of the leakage energy stored in the parasitic inductors.



a) b)

Figure 2: Example of: a:) low voltage transformer b:) high voltage transformer.

In the goal to resolve the critical problem of the stored leakage energy in the parasitic inductors an improvement was added to the initial structure as we can see in Fig.3. We can notice the addition of a secondary MOSFET M_2 driven in synchronisation with M_1 in order to flow-back via L_1 the over-stored energy. The analysis shows that this performed system presents two main advantages: 1) the perfect control of the recovery voltage V_c in the intermediate stage, 2) the possibility to decrease the direct voltage shut-down of the D_0 diode by a clever driving of the MOSFET M_2.

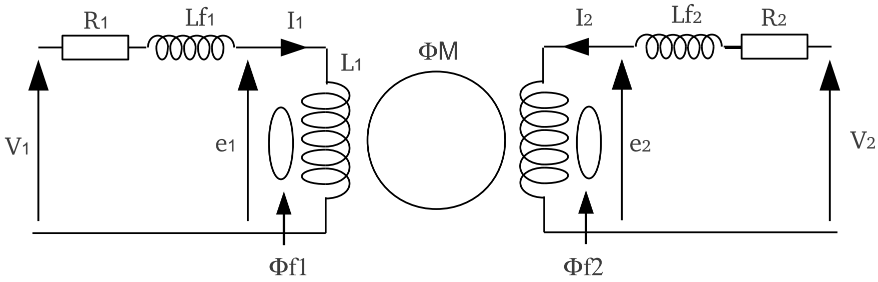


Figure 3: Equivalent electrical schematics of any two coils transformer.

2. Evolution of the recovering voltage Vc

Considering the improved MCB converter shown in Fig.2a, we propose to analyse the limit value of the coupling factor k, allowing a good stabilization of the V_c voltage when other parameters are imposed. This approach can be done using two main ways: 1) Using a simulation program like Orcad or Proteus, 2) A theoretical approach. A recent paper under submission describes precisely the dependence between k, V_e, V_{out}, m, and α, the duty cycle applied to the switch M_1.

2.1. Simulation approach

The simulation computed with Orcad software was established in accordance to the schematic reported in Fig.1b. The values for the components were fixed as:
$L_1 = 42\ \mu$H
$L_2 = 2058\ \mu$H
$m = 7$
$V_{in} = 20V$
$V_{out} = 400V$
$C = 10\mu F$
$k = 0.9$
D_0 schottky diode.

As we can observe on Fig.4, IL_1, IL_2 and I_c slopes, it is usable to identify four working times in the energy transfer. The current slopes obtained by simulation show a global behaviour and several main linear steps that are working identified modes analysed in anterior published papers. Those steps analysis are very useful for a theoretical approach. In Fig.5 are reported the voltage slopes of V_{ds} and V_{20} of the MCB converter. The maximum value of V_{ds} reaches a hundred of volts, added with a duty cycle value around 50%, which is conform with the principle of this converter The results of the simulation are a set of values corresponding to the variations of the coupling coefficient k. They are reported in Fig.6 and will be further compared to the theoretical approach results. Therefore, it clearly appears that the V_c voltage named for more convenience V_{cstab} is a negative coefficient dependency with k.

2.2. Theoretical approach

This theoretical analysis is based on the consideration of linear behaviour in the inductors, the coupled coils, capacitors and of course, the MOSFET static switch.
The initial equations for the transformer are the very classical linear equation system:

$$\begin{pmatrix} V_1(t) \\ V_2(t) \end{pmatrix} = \begin{bmatrix} L_{m1} + L_{k1} & M \\ M & L_{m2} + L_{k2} \end{bmatrix} \begin{pmatrix} \frac{dI_1}{dt} \\ \frac{dI_2}{dt} \end{pmatrix} \tag{1}$$

$$V_1 = V_{cstab} - V_e \tag{2}$$

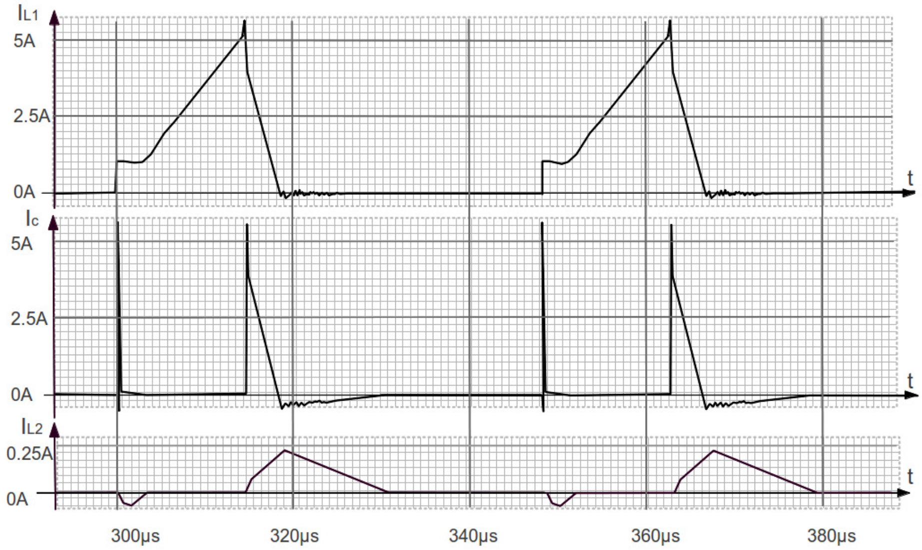


Figure 4: Simulation of the MCB recovery boost.

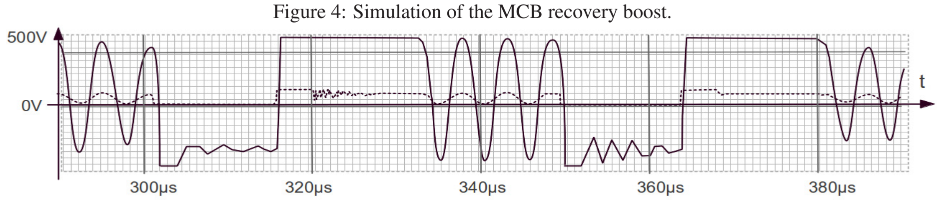


Figure 5: Chronograms of V_{20} and V_{ds} after stabilization.

$$\lambda = \left(\frac{\Delta V}{V_1} - 1\right) \tag{3}$$

$$V_1 = \frac{-V_e\left[(m-k) - \lambda\left(\frac{1}{m} - k\right)\right](\lambda k - m)\alpha k}{(1-\alpha)\left(\frac{\lambda}{m} - k\right)(\lambda k - m) + m\alpha(1-k^2)\left[(m-k) - \lambda\left(\frac{1}{m} - k\right)\right]V_e} \tag{4}$$

This equation needs a 3thrd degree resolution and can be easily solved with a numerical solver. The result of the computing is given in Fig 6 as a dash curve. A numerous resolution of this equation was made, fixing values for m, V_e, V_{out} and α as follows:
$m = 7$, $\Delta V = 380V$, $V_e = 20V$, $V_{out} = 400V$, $\alpha = 1/2$
After resolving, we obtain the V_1 values for each k value. Then we deduce V_c and the results are reported and superposed with the simulation results obtained before. For more convenience we name V_{cstab} the V_c voltage after stabilization, considering that the transitional evolution is not the aim of this study.

3. Comparison and conclusion of the V_c variations as a function of k

As we can observe on the results compiled in Fig.6, the simulation and the computation are coherent and show a global identical tendency of increasing V_c for the decreasing of k.

This important result clearly indicates that it is not possible to use this MCB structure when the coupling coefficient is lower than $k = 0.9$. Under that critical value of k, we observe that the intermediate V_{cstab} voltage rapidly inflates

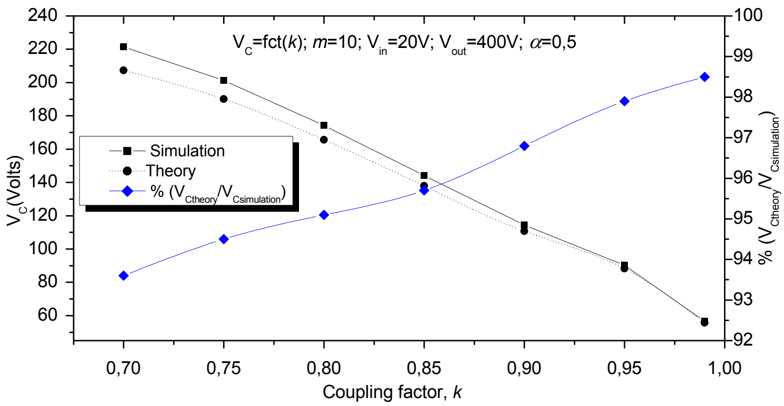


Figure 6: Evolution of V_{cstab} as a function of coupling factor k.

when the coupling factor k is decreasing and the Vc voltage value can be closer than the output voltage. We have to take in consideration that it is not possible to insure a correct working of the converter for high V_{cstab} values, because this voltage is directly applied to the MOSFET switch M_1 when D_0 is in on state. Consequently, as described in anterior papers [8, 9, 10, 11], the R_{dson} value of the MOSFET is lied to its maximum maintain voltage V_{dsmax} with a second order function. So, it is not interesting to consider value for V_{cstab} upper that a hundred of volts.

4. DC-DC coupled inductor boost converter with controlled recovery

4.1. Improved MCB converter for low coupling factor transformers

The consideration and characteristic in this converter concern two points: 1) The duty cycle applied to the main switch M_1 must be adjusted near to 50% in order to insure a good balance between the storage period and the restitution one. 2) The Vc voltage after stabilization (V_{cstab}) must be adjusted to a value around ($2xV_{in}$). That value is a good compromise and can be compared to the working mode of a basic boost step-up.
As shown is Fig.7, we can easily understand the advantage there is to decrease the direct voltage on D_0 by controlling the MOSFET M_2. In fact, it would be possible to choose D_0 as a Schottky type in the case of low V_c voltage value. We know that the direct voltage of a Schottky diode is about $0.2V$ to $0.4V$, depending on the current circulating in it, but the use of a parallel MOSFET presenting a low R_{dson} around few mW, implies a shut down voltage about few mV, that presents a better solution than a simple Schottky diode.

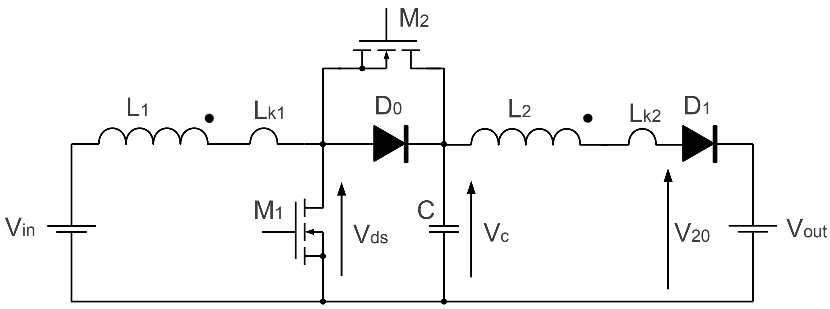


Figure 7: Improvement of the MCB recovery Boost by adding a second MOSFET.

The second advantage of this novel structure lies in the possibility of restitution into the input generator of the stored energy inside the capacitor C by controlling the on state of the MOSFET M_2, while maintaining M_1 the off state of course.

As mentioned before, the behaviour of this improved structure is based on the Fly-Back and basic step-up converter. A natural equilibrium between V_{in} , V_c and V_{out}. The magnetic coupling factor k of L_1 and L_2, the transformer ratio m constituted by the two coupled coils have an important effect on the stabilized voltage V_{cstab}. The simulation was done with the values used for anterior evaluation, but fixing a low value to k coefficient:
$L_1 = 42\mu H$, $L2 = 2058\mu H$, $m = 7$, $V_{in} = 20V$, $V_{out} = 400V$, $C = 10\mu F$, $k = 0.7$
The analysis of the currents curves in Fig. 8 shows two different steps:

- Step 1: Charge of capacitor C:
  We observe on Fig. 8 the increasing of V_c voltage capacitor when pulses are driven onto the switch M_1.
- Step 2: The V_c voltage capacitor falls down when the pulses disappear and M_2 is turned on.

We can observe in Fig. 8 the MOSFET drain voltage V_{ds} that oscillates between the saturation voltage value, i.e. $0V$, and a maximum one fixed by the V_c voltage. The output coil presents an amplified voltage clamped to $400V$ because imposed by the HVDC bus voltage which it is connected on. The relaxation oscillations observable on the signal are due to the parasitic inductors and MOSFETs capacitors.

By the way it is easy to understand that a precise control of M_1 and M_2 is absolutely necessary to insure the correct voltage evolution of V_{cstab}, and also the energy transfer from V_{in} to the HVDC bus. That implies the use of a multicontrol unit possibly assumed by a microcontroler for example.

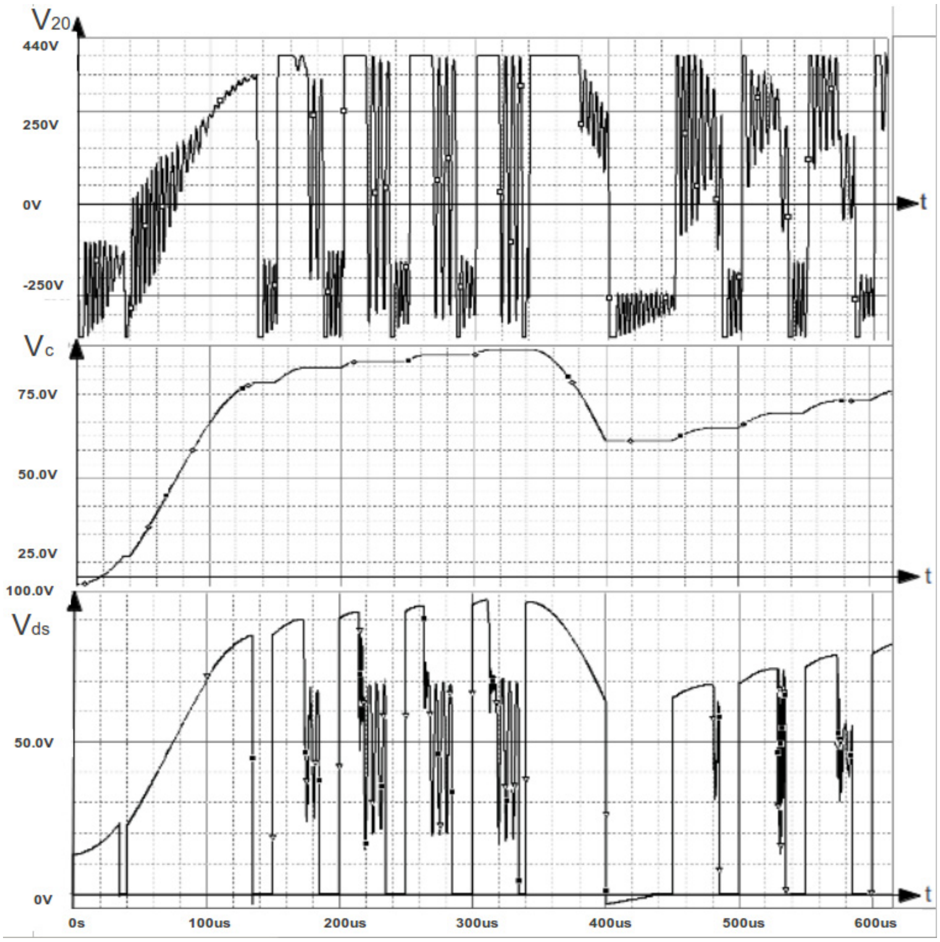


Figure 8: Chronograms of the voltages V_{ds}, V_c, V_{20}.

4.2. Application of the novel structure

An application of this improved double recovery MCB converter is proposed as an alternative solution to increase the global efficiency of the previous DC-DC converter. We can see in the global schematic in Fig. 9 that the MOSFETs drivers are independently controlled by two control inputs directly issue from a logic unit that is realised in our application by a micro-controller. We see in Fig.10, a concrete realisation of the transformer presenting a large distance between the primary and secondary coils to insure a correct galvanic isolation. The method used to measure the coupling coefficient is a double measurement on the coils connected in series, with magnetic opposition or not.

The difference between the two measurements is given by a basic equation Eq.5:

$$L_{low} = L_{high} - 4M \tag{5}$$

where L_{low} is the serial inductor measurement with opposite windings direction, L_{high} the serial measurement with same windings direction.

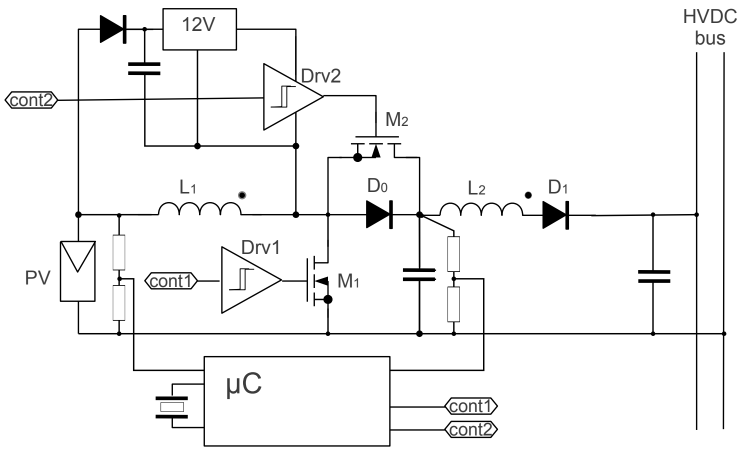


Figure 9: Implementation of the double recovery system in a MCB boost.

The measurement of the coupling factor M, Eq.5 is about 0.75 at $1kHz$, but it depends on the frequency used for it. The switching frequency is stabilized around $50kHz$, but it is not possible to insure that the k value is the same in our application frequencies. In fact, there is a propagation delay inside the ferrite, providing complex permeability and parasitic effects on the value of the magnetic parameters.

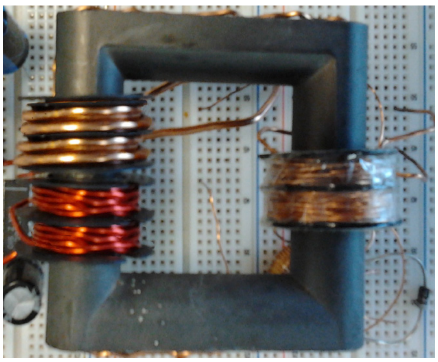


Figure 10: Realisation of the transformer.

5. Conclusion

The powerful conversion of high DC voltages from photovoltaic panels or wind generators into a HVDC grid implicates simple, reliable and cheap high efficiency converters. We previously proposed high voltage converters based on the MCB structure with recovery of the leakage energy. Until recently there was a technological lock in high efficiency Boosts. In the present study, we have shown that the use of a huge m ratio lowly coupled autotransformer is now possible if another switch is added in parallel with the recovery diode in the anterior system. Then a specific management of the two active switches combined together with an imperative control of the Vc voltage must be developed in the embedded micro-controller software. In the case of a PV panel or a wind turbine application, the software must assume the MPPT, the voltages and currents control, the PWM MOSFET M_1 management associated with the MOSFET M_2 recovery system. As in the previous MCB converter, the duty cycle is basically adjusted near 50% that presents the most efficient ration to the energy transfer. This novel system needs to be characterized more specifically to validate the perfect behaviour for low values of k and high output voltage.

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